Investigation of Wide Bandgap Materials for Cold Electron Emission

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Outline

I. Cold Cathode Development - Challenges and Issues

II. Wide Bandgap Emitter Materials

III. Technical Approach
  - Surface Characterization
  - Transport and Emission Studies
  - Injection Models

IV. Novel Materials

V. Conclusions

Challenges: Cold Cathode Technology

Innovative Cold Electron Sources Must Be Developed That Provide:

- **High current density J**
- **Uniform emission**
- **Robust emission**
- **Low voltage operation**
- **Emission modulation**

High-performance Cold Cathodes Are Needed to Enable Next-generation Vacuum Electron Devices with:

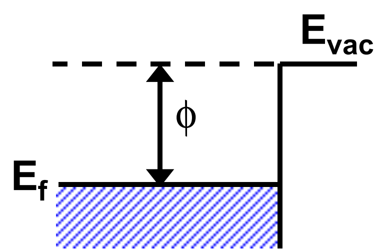
- **Higher power**
- **More compact size**
- **Increased efficiency**
- **Longer life**

Emission Process in Cathode Materials

Emission Process

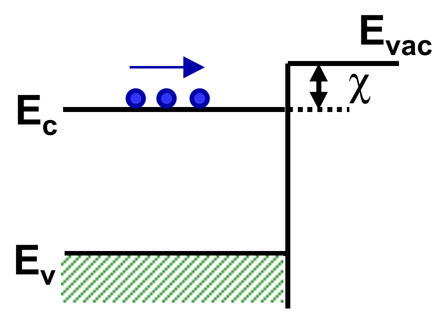
- Escape across surface barrier
- Electron supply mechanism

Metal



$\phi = E_{vac} - E_f$
(work function)

Semiconductor or Insulator



$\chi = E_{vac} - E_c$
(electron affinity)

Material	Emission type	Surface barrier	Electron supply
metal	thermionic	ϕ	conduction e-s
	field emission	tunneling	conduction e-s
non-metal	field emission	tunneling	valence e-s
	cold (low field)	χ	conduction e-s

$\Rightarrow$ need low or negative electron affinity (NEA)

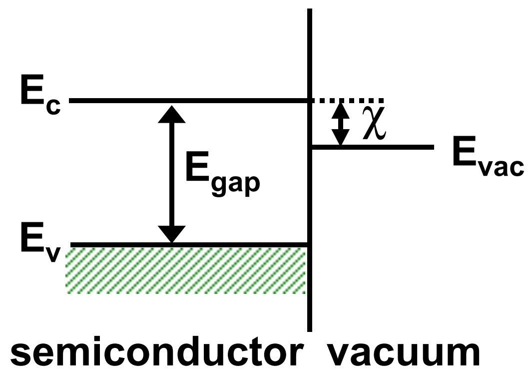
Wide Bandgap Materials

Materials

Diamond $E_{gap} = 5.5$ eV

$Al_xGa_{1-x}N$ $3.4 \leq E_{gap} \leq 6.2$ eV
$(0 \leq x \leq 1)$

$\chi = E_{vac} - E_c$



NEA Surface Properties

Diamond $\chi < 0$

$Al_xGa_{1-x}N$ $\chi < 0$ for $x > 0.75$

Electron Transport Properties

- High current density: $J \sim 10^3 - 10^5$ A/cm^2
- High electron mobilities: $\mu \sim 1600$ cm^2/V-s (diamond)
  ~ 1200 cm^2/V-s (GaN)
- High breakdown fields: $E \sim 8 \times 10^6$ V/cm (diamond)
  $\sim 3 \times 10^6$ V/cm (GaN)

Opportunities in Cold Cathode Development

Materials

Wide Bandap Materials: Diamond, III-Nitrides

- $\rightarrow$ **high-electron-density transport**
- $\rightarrow$ **small or negligible surface barrier**

Growth / Fabrication Capabilities

- **Molecular Beam Epitaxy (MBE)**
- **Chemical Vapor Deposition (CVD)**
- **Doping Control**
- **Heterostructures and Multi-layer structures**

Cold Emission Process

The development of wide bandgap cold emitter materials must address the 3 steps involved in the emission process:

Injection → Transport → Emission

Injection: **Develop injection mechanism to maintain electron supply in conduction band**

Transport: **Determine influence of material properties on the intensity and energy distribution of transmitted electrons**

Emission: **Identify stable low or negative electron affinity surfaces and characterize emitted electron distribution**

Approach: Cold Cathode Development

1) Evaluate Transport and Emission Processes

If electrons are present in the conduction band:

- How efficient is emission at NEA surface?
- What are the electron emission characteristics?
- How do the bulk and surface properties affect the emission?

2) Develop Cathode Structures to Supply Conduction Electrons

- How are electrons injected into the conduction band?
- How is electron supply maintained?

Studies: Surface and Transport Properties

Surface Studies (Diamond: B. Pate-WSU, R. Nemanich-NCSU, J. Robertson-Cambridge,)
(III-Nitride: A. Kahn-Princeton, R. Nemanich-NCSU, V. Bermudez-NRL,)

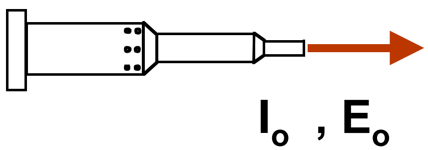
material	χ (eV)	stability
bare C	~0.5	heat to T > 1000 °C to clean
H/C	- (1.0-2.0)	stable to T ~ 1000°C
Bare GaN	+3.3	N-sputter & anneal (1100°C) to clean
Bare AlN	< 0 to +1.9	very reactive
Cs	-0.7	?

Electronic Studies (P. Cutler-PSU, P. Mumford-AF-WL,)

Diamond: Ballistic electron transport through conduction band
Transport through defect states or bands also possible

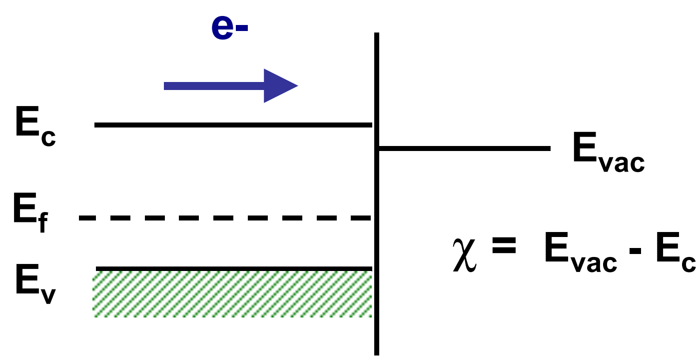
III-Nitrides: Ballistic transport through conduction band

NRL Studies: Transport and Emission



INJECTION

Impacting e- beam



TRANSPORT   EMISSION

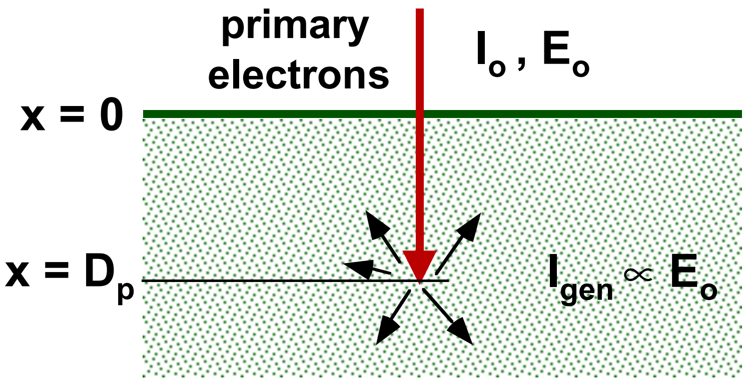
- **Injection of high-energy electrons into material using e- gun**
- **Transport and Emission of low-energy electrons at NEA surface**
- **Measurements: Energy distribution curves**
  Secondary yield curves

Techniques

- **Secondary electron emission spectroscopy**
- **Transmission electron spectroscopy**

Secondary Emission Process In Wide Bandgap Material

Generation of secondary electrons



As E_o Increases:

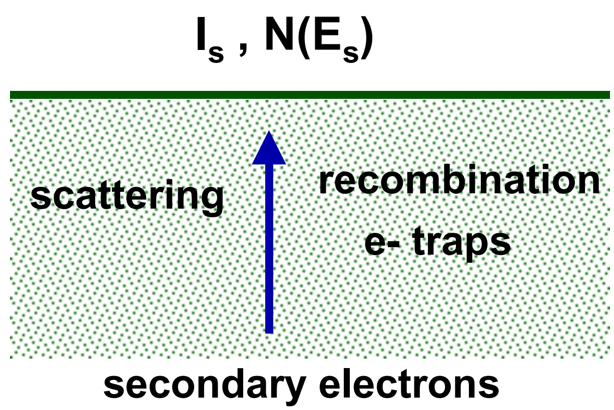
Penetration Depth Increases

⇓

Generation Depth Increases

Generated Current Increases

Transport to and emission at surface



Transport Process

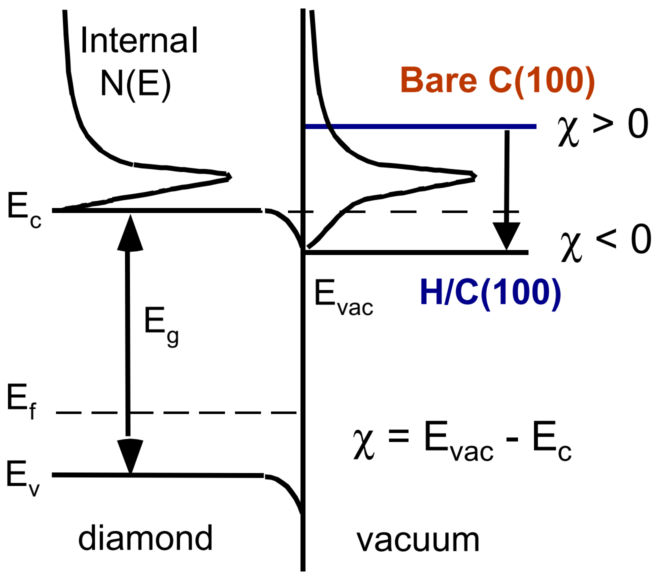
⇓

Inelastic Scattering → Energy Loss

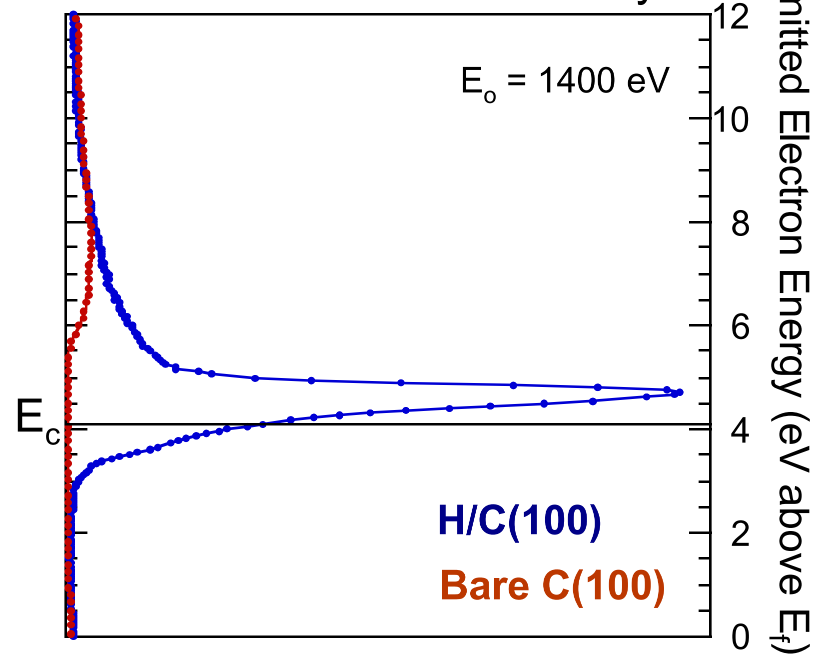
Recombination/Traps → Intensity Loss

Low-Energy Electron Emission From Diamond

Emission Model



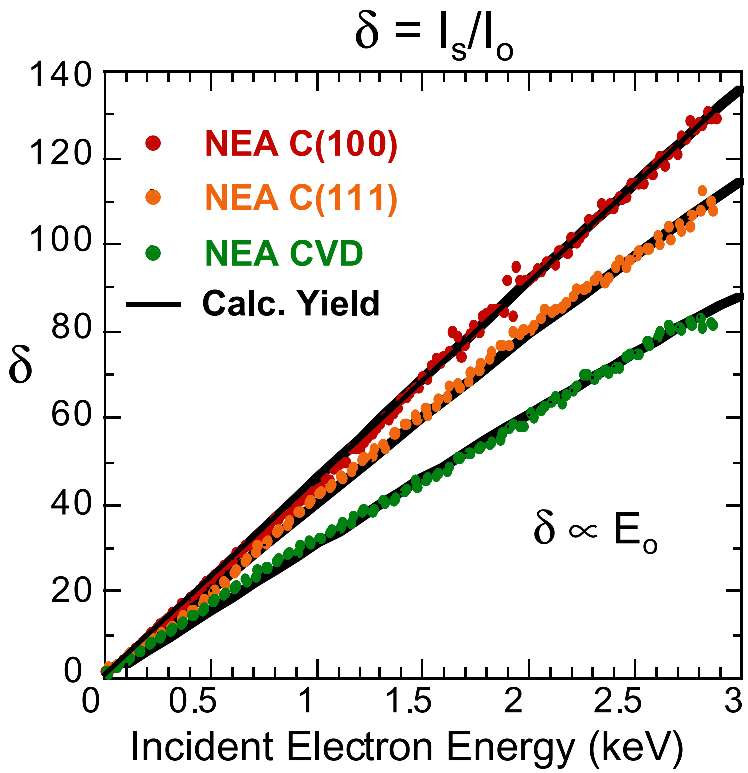
Emitted Electron Intensity



- **Emitted energy distribution is sensitive to χ**
- **Electron distribution dominated by low-energy electrons**
  $\Rightarrow$ FWHM ~ 0.5 eV, <KE> ~ 0.5 eV

Cold low-e nergy electrons are emitted efficiently at NEA surface

Efficient Transport of Low-Energy Electrons in Diamond



- **Extremely high yields**

  $\rightarrow$ δ ~ 90 - 130 !!

- **δ increases with increasing E_o**

  $\Rightarrow$ D_{esc} >> 0.13 μm

- **Secondary yield calculations:***

  $\Rightarrow$ D_{esc} ~ 1 - 5 μm

* Martinelli and Fisher, Proc. IEEE **62**, 1339 (1974)

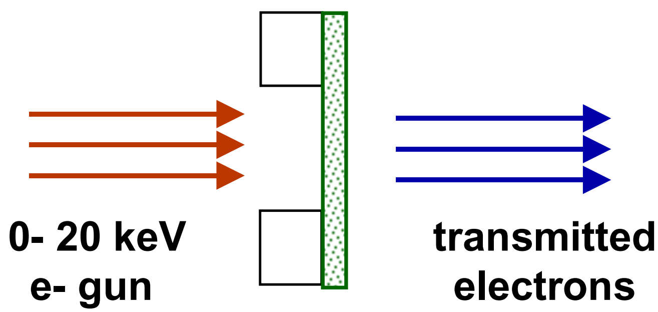
Low-energy electrons have long escape depths in diamond samples

$\Rightarrow$ **Examine transport process more directly in transmission studies**

Electron Transmission Studies

Experimental Approach

CVD diamond film on Si substrate*
⇒ Si etched to create diamond window

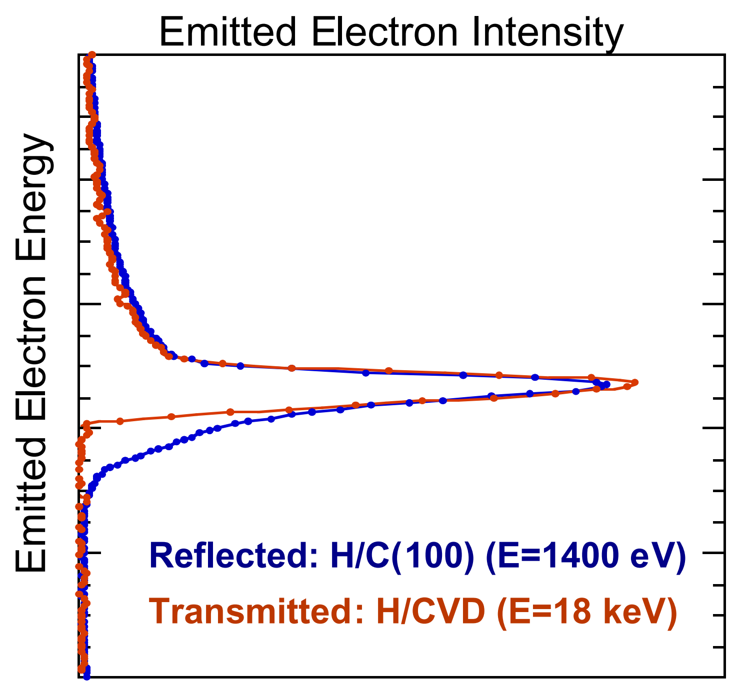


Thickness
1 - 10 μm

B-doping
low → high

- Determine effect of dopants on transport
- Determine escape depth of secondary electrons

* J. Butler and P. Pehrsson, NRL



Initial Studies
Energy distribution is nearly identical in reflection and transmission measurements

⇒ Need to understand factors that limit transmitted *current*

Approach: Cold Cathode Development

1. Evaluate Transport and Emission Processes
   - Low-energy electrons are emitted very efficiently at NEA surfaces
   - Energy distribution is sharply peaked at very low KE
   - Low-energy electrons have long escape depths in diamond

     → Influence of bulk properties is under investigation

     → Emission at III-nitride surfaces is under investigation

2. Develop Cathode Structures to Supply Conduction Electrons
   - How are electrons injected into the conduction band?
   - How is electron supply maintained?

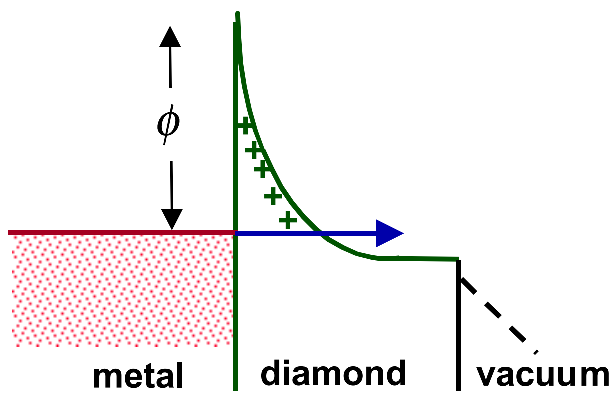
Various Injection Models Under Theoretical & Experimental Investigation

Internal Field Emission Model in Diamond

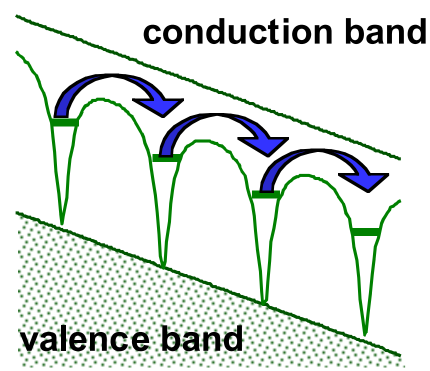
Main Barrier to Emission Is at Back Contact

Approach: **Dope with N impurities (deep donor levels)**

$\rightarrow$ **Depletion layer created at back contact that produces band bending and narrowing of the barrier**



model 1



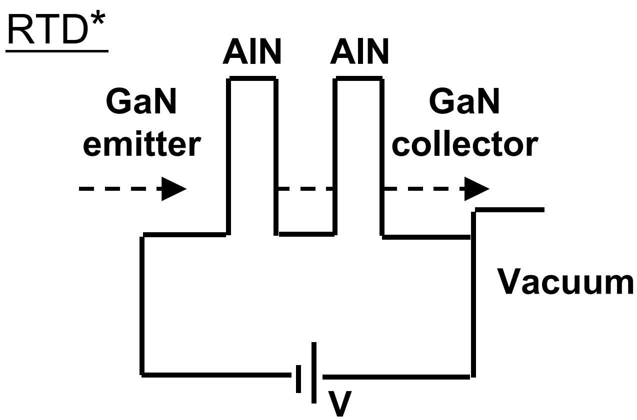
model 2

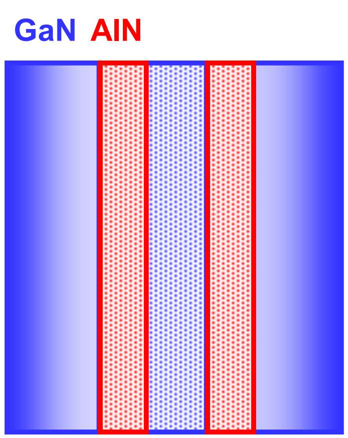
Transport Under Applied Field

model 1: electrons tunnel through to conduction band (M. Geis, MIT-LL)

model 2: electrons hop through gap via impurity or defect levels (A. Gohl)

Resonant Tunneling Diode (RTD) Emitter





RTD based on AlN/GaN/AlN quantum well

Tunneling Transport Characteristics

- narrow energy distribution
- narrow momentum distribution
- J_{max} ~ 300 kA/cm^2 (reported for InAs/AlSb)

Predicted Emission Characteristics

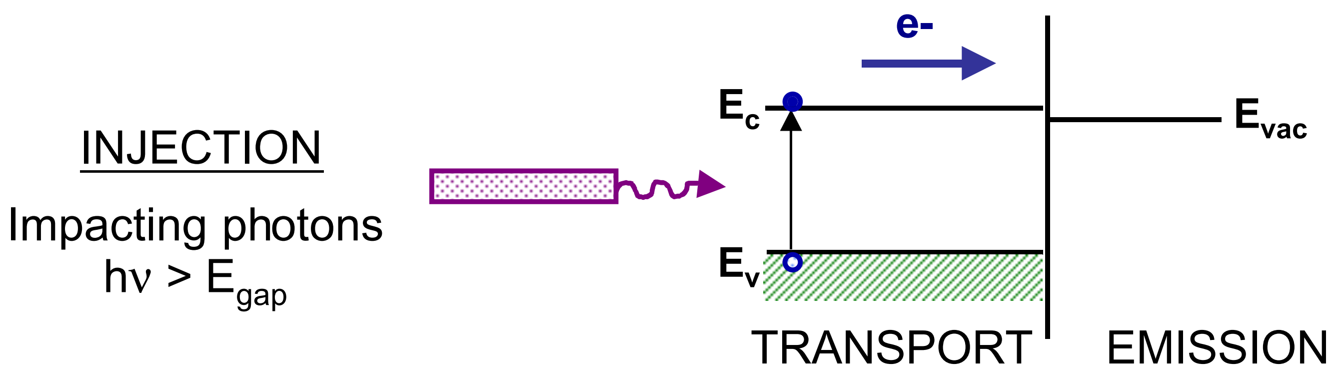
- monoenergetic beam
- highly-collimated beam
- beam modulated by V

Key Issues

- Current density through AlGaN RTD
- Effect of impurities and defects
- Small surface barrier

*S. Krishnamurthy, SRI International

Photo-injection Mechanism



III-Nitrides are *direct* bandgap materials $\Rightarrow$ Opto-Electronic Devices

<u>Advantages of external photon source</u>

- **Emitter structure is less complex, easier to optimize**
- **Laser provides injection and modulation capabilities**

<u>Disadvantages of external photon source</u>

- **Cathode-laser system is cumbersome**
- **Higher input power demands**

***Internal* photon source possible $\Rightarrow$ Complex heterostructure design**

Status: Wide Bandgap Emitter Materials

Material Issues $\Rightarrow$ Key to Successful Cold Cathode Development

Diamond: Material Challenges

- **n-type doping - shallow donor**
  - $\rightarrow$ Reduced Schottky barriers or ohmic back contacts
- **Reproducible high-quality CVD diamond growth**

III-Nitrides: Material Challenges

- **Surface preparation for low or negative χ**
  - $\rightarrow$ Investigate electronic structure of AlN and AlGaN alloy surfaces prepared under various conditions
- **Reduce defects/dislocations**
  - $\rightarrow$ Study scattering mechanisms and transport in specific materials and device structures
- **Improved control of doping (p-type, n-type contaminants)**

Novel Emitter Materials

Other Carbon Materials:	**Diamond-like Carbon** **Nano-crystalline Diamond** **Carbon Nanotubes**

- √ **Harsher growth conditions are allowed**
- √ **Cheaper fabrication processes can be used**
- √ **Novel materials are produced**

But ... material properties may not be well understood

- → **Emission model?**
- → **Uniformity?**
- → **Reproducibility?**

Amorphous and Nano-Crystalline Carbon

Diamond-like Carbon (DLC)

Amorphous semiconductor with sp^3 (diamond) and sp^2 (graphite) bonds

E_{gap} ~ 1 - 4 eV ($\chi\downarrow$ as $E_{gap}\uparrow$); ϕ ~ 3.5 - 4.0 eV

High density of defects

Nano-grained CVD Diamond

Nano-crystalline grains ~ 50-100 nm

High density of conducting grain boundaries

Graphitic phase at boundaries with ϕ = 4.7 eV

Main Emission Barrier Is at Front Surface $\rightarrow$ Need to Tunnel Across Barrier

Very high fields can be created at C surfaces due to:

- nm-size surface regions with different termination $\Rightarrow$ High local fields
- High defect density causes short depletion width $\Rightarrow$ High near-surface fields
- High breakdown fields in diamond-like material

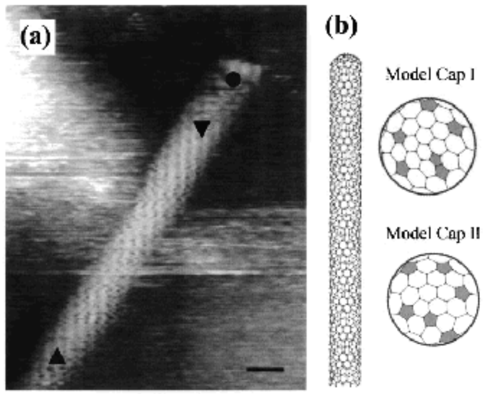
DLC: Dope with N (shallow donor) to decrease ϕ; increase sp^3 content to decrease χ

CVD: Field enhancement at conducting grain boundaries, surface roughness

Carbon Nanotubes

<u>Nanotubes</u>: sp^2-bonded rolls of graphite

- Similar electronic structure to DLC
- High-density arrays of aligned nanotubes

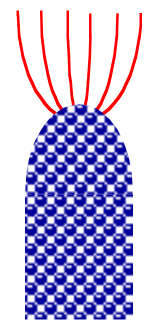


<u>Field Emission Studies</u> (W. Zhu, Lucent)

Best emission from single-walled nanotubes (swnt)
J_{max} ~ 1 - 5 A/cm^2
Emission site density ~ 10^4 cm^{-2}

<u>Cathode Issues</u>

- **Emission due to small tube size**
  - ⇒ Characterize emission as function of tube size
  - ⇒ Determine optimum array structure
- **Low adsorbate sensitivity**
  - ⇒ Determine effect of tube size, structure on reactivity
- **Extremely rigid, strong and possibly self-healing**
  - ⇒ Determine robustness in sputtering environment



swnt diam.
~ 1-5 nm

Future Prospects for Cathode Development

Steady advances in materials growth, fabrication, and design are expected due to:

- powerful new characterization tools
- precision instrumentation for controlled growth
- deeper understanding of material properties

Near-term Prospects

Improvements in the quality and control of wide bandgap materials will enable the development of high-performance cold cathodes for specific device applications and operating environments

Long-term Prospects

Potential for new classes of materials, new structures, and new emission mechanisms